

2025 Fall Introduction to ODE

Homework 8 (Due November 10 12:00, 2025)

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Exercise 1. Suppose a, b, c are nonnegative continuous functions on $[0, \infty)$, u is a nonnegative bounded continuous solution of the inequality

$$u(t) \leq a(t) + \int_0^t b(t-s)u(s) ds + \int_0^\infty c(s)u(t+s) ds, \quad t \geq 0,$$

and $a(t) \rightarrow 0$, $b(t) \rightarrow 0$ as $t \rightarrow \infty$, $\int_0^\infty b(s) ds < \infty$, $\int_0^\infty c(s) ds < \infty$. Prove that $u(t) \rightarrow 0$ as $t \rightarrow \infty$ if

$$\int_0^\infty b(s) ds + \int_0^\infty c(s) ds < 1.$$

Solution 1.

Steps:

1. Choose a sequence that approaches the limsup of $u(t)$ as $t \rightarrow \infty$.
2. Split the integral appropriately and estimate the terms.
3. Combine everything and show that the limsup must be zero.

Method:

1. Let $\{t_n\}_{n \in \mathbb{N}}$ be a sequence such that $t_n \rightarrow \infty$ as $n \rightarrow \infty$ and $u(t_n) \rightarrow L = \limsup_{t \rightarrow \infty} u(t)$. By a change of variables, we have

$$u(t) \leq a(t) + \int_0^t dr b(r)u(t-r) + \int_0^\infty ds c(s)u(t+s).$$

2. Since $b(t) \geq 0$ and $\int_0^\infty ds b(s) < \infty$, we have $\lim_{R \rightarrow \infty} \int_R^\infty ds b(s) = 0$. This holds similarly for $c(t)$, so there exist $R_b, R_c > 0$ such that

$$\int_{R_b}^\infty ds b(s) < \varepsilon, \quad \int_{R_c}^\infty ds c(s) < \varepsilon.$$

By the definition of L , there exists $T_\varepsilon > 0$ such that $u(t) \leq L + \varepsilon$ for all $t \geq T_\varepsilon$. Let's take $T = T_\varepsilon + \max\{R_b, R_c\}$, and n sufficiently large such that $t_n \geq T$.

3. Now we will estimate each term at $t = t_n$: First, since $a(t) \rightarrow 0$ as $t \rightarrow \infty$, there exists $N_1 \in \mathbb{N}$ such that for all $n \geq N_1$, we have $a(t_n) < \varepsilon$. Next, we split the first integral:

$$\int_0^{t_n} dr b(r)u(t_n - r) = \int_0^{R_b} dr b(r)u(t_n - r) + \int_{R_b}^{t_n} dr b(r)u(t_n - r).$$

The first term is bounded by $(L + \varepsilon) \int_0^{R_b} dr b(r)$, and the second term is bounded by $M \int_{R_b}^\infty dr b(r) < M\varepsilon$, where $M = \sup_{t \geq 0} u(t)$. Similarly, we split the second integral:

$$\int_0^\infty ds c(s)u(t_n + s) = \int_0^{R_c} ds c(s)u(t_n + s) + \int_{R_c}^\infty ds c(s)u(t_n + s).$$

The first term is bounded by $(L+\varepsilon) \int_0^{R_c} ds c(s)$, and the second term is bounded by $M \int_{R_c}^\infty ds c(s) < M\varepsilon$. Combining everything, we have for all n sufficiently large,

$$\begin{aligned} u(t_n) &\leq a(t_n) + \int_0^{t_n} dr b(r)u(t_n - r) + \int_0^\infty ds c(s)u(t_n + s) \\ &= \varepsilon + (L + \varepsilon) \int_0^{R_b} dr b(r) + M\varepsilon + (L + \varepsilon) \int_0^{R_c} ds c(s) + M\varepsilon \\ &= (L + \varepsilon) \left(\int_0^{R_b} dr b(r) + \int_0^{R_c} ds c(s) \right) + \varepsilon(1 + 2M). \end{aligned}$$

Rearranging gives

$$L \leq \frac{1 + B + C + 2M}{1 - (B + C)} \varepsilon,$$

where $B = \int_0^\infty dr b(r)$ and $C = \int_0^\infty ds c(s)$. Since $\varepsilon > 0$ is arbitrary, we conclude that $L \leq \limsup_{t \rightarrow \infty} u(t) = 0$. Since $u(t) \geq 0$, we have $\lim_{t \rightarrow \infty} u(t) = 0$.

Exercise 2. For any real matrix D , $\det D \neq 0$, show there is a real matrix B such that $e^B = D^2$. If C is a real matrix in Lemma 7.1 and there is a real matrix B such that $e^B = C$, must there exist a real matrix D such that $C = D^2$?

Solution 2.

Steps:

1. Show the existence of B such that $e^B = D^2$ using Jordan canonical forms.
2. Discuss whether there must exist a real matrix D such that $C = D^2$.

Method:

1. Let $D \in M_n(\mathbb{R})$ be a real invertible matrix. Let λ be an eigenvalue of D with eigenvector v , so $Dv = \lambda v$. Then, we have

$$D^2v = D(\lambda v) = \lambda Dv = \lambda^2 v.$$

Therefore, the eigenvalues of D^2 are $\lambda_i^2 > 0$, where λ_i are the eigenvalues of D and are nonzero since $\det D \neq 0$. In its Jordan canonical form J such that $D = PJP^{-1}$, let B be the matrix such that each Jordan block corresponding to eigenvalue λ_i^2 is replaced by a Jordan block corresponding to eigenvalue $\log(\lambda_i^2)$. Denote this Jordan form by J_B , and we have

$$D^2 = PJ^2P^{-1} = Pe^{J_B}P^{-1} = e^{PJ_BP^{-1}} = e^B.$$

Thus, such a real matrix B exists.

2.

Lemma 1 (Hale, Lemma 7.1). If C is an $n \times n$ matrix with $\det C \neq 0$, then there is a matrix B such that $e^B = C$.

That is, any invertible matrix has a logarithm. We will show that any such matrix has a square root as well. Since there is a matrix B such that $e^B = C$, consider the matrix $D = e^{B/2}$, then

$$D^2 = e^{B/2}e^{B/2} = e^B = C$$

since $\frac{B}{2}$ commutes with itself. Thus, such a real matrix D exists.

Exercise 3. Let $X = X(t) \in \mathbb{R}^{n \times n}$ be the fundamental matrix solution of $E\dot{x} = H(t)\vec{x}$, where E is given by

$$E = \begin{pmatrix} 0 & I_k \\ -I_k & 0 \end{pmatrix}$$

and $H = H(t)$ is symmetric and periodic with period T . Suppose H is a nonconstant matrix, and let $\mathbb{H} = \{X(t) : t \in \mathbb{R}\}$. Must \mathbb{H} be a subgroup of the symplectic group $G := \{M \in \mathbb{R}^{2k \times 2k} : M'E'M = E\}$? Justify your answer. Here, M' denotes the transpose of the matrix M .

Solution 3.

Steps:

1. Show that $X(t)$ is symplectic for all $t \in \mathbb{R}$, and hence $\mathbb{H} \subseteq G$.
2. Show that \mathbb{H} is not closed under matrix multiplication with a counterexample. Hence, \mathbb{H} is not a subgroup of G .

Method:

1. Let $X(t)$ be the fundamental matrix solution of the system $E\dot{x} = H(t)\vec{x}$. We will show that $X(t)$ is symplectic for all $t \in \mathbb{R}$. Consider the matrix $Y(t) = X(t)'EX(t)$. Differentiating $Y(t)$ with respect to t , we have

$$\frac{dY}{dt} = \dot{X}(t)'EX(t) + X(t)'E\dot{X}(t).$$

Taking transpose of $\dot{X}(t) = E^{-1}H(t)X(t)$, we have $(EX)' = (H(t)X)'$. Using $E' = -E$, $H' = H$, we get $\dot{X}'E = -X'H$. Substituting back gives $\dot{Y} = 0$. At $t = 0$, $X(0) = I$, so $X'(0)EX(0) = Y(0) = I$. Therefore, $X(t)$ is symplectic for all $t \in \mathbb{R}$, and $\mathbb{H} \subseteq G$.

2. To show that \mathbb{H} is not a subgroup of G , we will show that matrix multiplication is not closed in \mathbb{H} by constructing a counterexample with $k = 1$. Let

$$E = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

and $H(t) = \sin tI_2$, where I_2 is the 2×2 identity matrix. Then $H(t)$ is non-constant in time, symmetric, and periodic with period 2π . The system $E\dot{x} = H(t)x$ can be written as

$$\begin{cases} \dot{x}_2 = \sin tx_1, \\ \dot{x}_1 = -\sin tx_2, \end{cases}$$

which is easily solved by the change of variable $z = x_1 + ix_2$. The solution is

$$z(t) = z(0) \exp \left(\int_0^t \sin s \, ds \right) = z(0)e^{i(1-\cos t)},$$

and the fundamental matrix solution is a rotational matrix given by

$$X(t) = \begin{pmatrix} \cos \theta(t) & -\sin \theta(t) \\ \sin \theta(t) & \cos \theta(t) \end{pmatrix}, \text{ where } \theta(t) = 1 - \cos t.$$

As can be seen, $X(t)$ is symplectic, and since $\cos t \in [-1, 1]$, $\theta \in [0, 2]$, our set \mathbb{H} is given by

$$\mathbb{H} = \{X(t) \mid t \in \mathbb{R}\} = \left\{ \begin{pmatrix} \cos \phi & -\sin \phi \\ \sin \phi & \cos \phi \end{pmatrix} \mid \phi \in [0, 2] \right\}.$$

Now, pick t_1, t_2 such that $\phi_1 = \theta(t_1)$, $\phi_2 = \theta(t_2)$ are equal to $\frac{3}{2}$. Then, by property of rotation matrices, we have

$$X(t_1)X(t_2) = \begin{pmatrix} \cos 3 & -\sin 3 \\ \sin 3 & \cos 3 \end{pmatrix},$$

where none of $3 + 2n\pi$ lies inside $[0, 2]$. Therefore, $X(t_1)X(t_2) \notin \mathbb{H}$, and \mathbb{H} is not closed under matrix multiplication. Thus, \mathbb{H} is not a subgroup of G .